“Forms of wearable computer”, S. I. Woolley, J. W. Cross, S. Ro, R. Foster, G. Reynolds, C. Baber, H. Bristow and A. Schwirtz, IEE Eurowearable 2003 Conference, September 2003.

DOI: http://dx.doi.org/10.1049/ic:20030146

"Count three for wearable computers", Sandra Woolley, James Cross, Soonghwan Ro, Rob Foster, Greg Reynolds et al., Electronics Systems and Software, vol. 2, no. 1, pp. 34 – 38, February 2004

DOI: http://dx.doi.org/10.1049/ess:20040106

FORMS OF WEARABLE COMPUTER

S. I. Woolley, J. W. Cross, S. Ro, R. Foster, G. Reynolds, C. Baber, H. Bristow, A. Schwirtz

Electronic, Electrical and Computer Engineering, The University of Birmingham, U.K.

ABSTRACT

This paper introduces the microprocessor, communicating and sensing technologies relevant to wearable computing. It reviews the trends and challenges that form part of the evolution of computer technology, from a computer filling a room to a room full of invisible computers.

Not all wearable computing systems require the same level of computing performance or functionality. A Processor Performance and Flexibility of Function (PPaFF) scale is introduced to classify wearable computing systems and is related to the prototypes described in Weiser's vision of the 21st century computer.

1. INTRODUCTION

1.1. Wesier's 21st Century Computer

The late Mark Weiser, a chief technology officer at Xerox's Palo Alto Research Centre, first coined the term 'ubiquitous computing' in 1988 to describe his vision of a future when invisible computers, embedded into everyday objects, would replace PCs. His ideas were summarised in a Scientific American article, "The Computer for the 21st Century" (1). The recent first issue of the new IEEE Pervasive Computing Magazine (2) was dedicated to the late Mark Weiser and the vision he reported in Scientific American.

Weiser envisioned ubiquitous computers of different sizes, suited to different tasks. He described three sizes of laboratory prototypes, which he called *tabs*, *pads* and *boards* and described as active versions of equivalent-sized conventional media:

- tabs: post-it scale;
- pads: paper or book scale;
- boards: blackboard scale;

The *tab* prototype was a kind of active badge with calendar and diary functionality. The *pad* was described as analogous to scrap paper for the swappable manipulation of desk objects or projects. A *board* could be an active bookcase for documents or videos in the office or at home.

He suggested that, in the future, rooms might contain more than 100 tab-like computers, 10 or 20 tabs and 1 or 2 boards, observing that "*Hundreds of computers in a room could seem intimidating at first, just as hundreds of volts coursing through wires in the walls once did.*" Since then his vision of so many embedded computer systems appears to be correct, with many systems throughout the home now being microprocessor-controlled, even down to the toaster.

He also anticipated the evolution of terabyte storage solutions and the development of more compact "*micro-kernel*" operating systems running software that could be readily added and removed. Considering wireless technologies, he observed that "*Present technologies would require a mobile device to have three different network connections: tiny-range wireless, long-range wireless and very high speed wired. A single kind of network connection that can somehow serve all three functions has yet to be invented.*" Again, we have seen much development here also, with the development of Bluetooth and Wi-Fi wireless solutions.

2. MICROPROCESSOR EVOLUTION

Achieving Weiser's vision of invisibly embedded computers relies on the continuing evolution of microprocessor technology, as well as power management and wireless networking solutions.

Figure 1: ENIAC, an early room-filling, 30 ton, 140 kilowatt computer at the University of Pennsylvania.

Colossus, the world's first computer, was secretly built during WWII for the purpose of cracking encrypted military signals. It was soon followed by Mark I (or "Baby") at Manchester University, U.K. and ENIAC (the 'Electronic Numerical Integrator and Computer') at the University of Pennsylvania, U.S.A.

With a monumental reduction in size, weight and power consumption, computing power approximately equivalent to ENIAC was realised by the world's first microprocessor.

Founded in 1968, Intel began as a tiny start-up company in Santa Clara, U.S.A., with ambitions to sell electronic memory products. With little design experience, the company decided to meet a 1970 order from the Japanese calculator company, Busicom, with a general-purpose processing solution. This resulted in the Intel 4004, the world's first microprocessor; a 4-bit general-purpose silicon computing chip with approximately the same performance as ENIAC.

Intel's processing evolution continued and in 1981, IBM selected the Intel 8088 for their new desktop PC computer. In 1986 Intel provided their first 32-bit variant the 80386 and later the Pentium in 1993.

The observation made by Intel founder, Gordon Moore, that computing capacity doubled approximately every 2 years, is now well-known as "Moore's Law" and has held true for some 30 years (3).

2.1 Portable and Mobile Computing

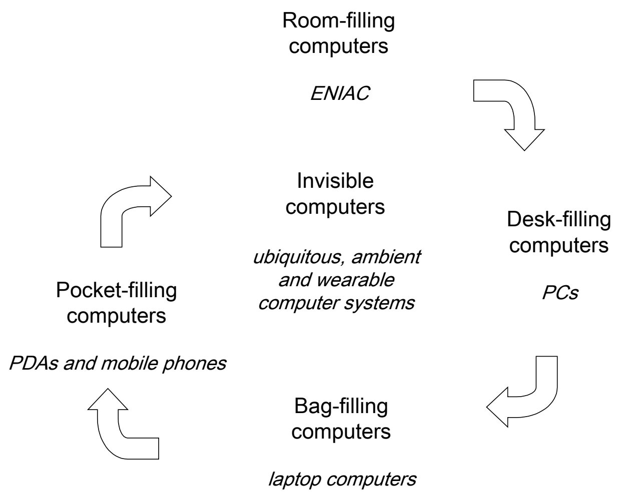

Figure 2: The evolutionary process from computers filling a room to a room full of invisible computers.

As shown in Figure 2, the evolution of computer technology has produced portable and mobile devices, taking the computer from the desk into the bag in the form of laptops and tablet PCs, and into the pocket in the form of PDAs (personal digital assistants) and mobile telephones.

Making pocket-sized computing and communicating systems has required significant improvements in both processor performance and power management whilst battery technologies have also been steadily increasing.

2.2 Embedded Microprocessor Intelligence

As well as the evolution of microprocessors and systems for general-purpose computing, two important processor variants also evolved in parallel:

- Digital Signal Processors (DSPs) - processors specifically designed for efficient execution of the mathematical operations required of signal processing (e.g., audio and video coding);

- Microcontrollers - compact, rugged-ised, low-power processors designed to be *embedded* into systems for control applications (e.g., automotive control).

In engineering terminology, an *embedded system* is any system or everyday object that has embedded processor intelligence *for purposes other than general purpose computing.*

Ubiquitous or pervasive computing systems can therefore be classed as embedded systems, with wearable systems being a special subset where the embedded object is the wearer.

The embedded systems market has grown rapidly in recent years with efficient, low-power 8-, 16- and even 32-bit microcontrollers being embedded in ever larger numbers, in cars and modern electrical appliances for the home. They are also increasingly found in a wide range of personal electronic consumer goods and gadgets (for example, watches and interactive toys).

3. AMBIENT AND CONTEXT-AWARE COMPUTING

Ambient and context-aware computing are active research areas relevant to the realisation of invisible ubiquitous computers. Both require embedded intelligence from the use of multiple, co-operating wireless sensing units, and can perhaps be distinguished by the flow direction of sensing intelligence:

- **Ambient intelligence** - sensing intelligence is embedded *into* the environment;

- **Context-awareness** - sensing intelligence is extracted *from* the surrounding environment (and objects within it).

3.1 Sensors And Sensing

Whether the technology is ambient intelligent or a context aware, both require the ability to sense their surroundings.

Activity sensors such as accelerometers and gyroscopes detect force and rotation that makes them useful for sensing movement and inferring activity types.

Location sensors such as GPS (Global Positioning System) can provide outdoor position within metres by triangulating signals from satellites. Locally and indoors, more accurate positioning can be achieved by a variety of sensing arrays. Activity sensors can also be used to estimate location.

Bio-sensors can measure heart rate, pulse, temperature and blood pressure and can be used for healthcare monitoring, sports, or to infer a person's mood or emotional state; referred to as affective computing.

4. WIRELESS TECHNOLOGY

Weiser quite rightly observed the importance of wireless technology evolution for mobile computing.

Wireless technologies are primarily *radio* or *infrared*, i.e., electromagnetic waves in the Radio Frequency (RF) or InfraRed (IR) spectrum. Examples of infrared communicators are TV remote controllers or IrDA® (InfraRed Data Association Standard) ports on some portable devices. The disadvantage of using infrared is that it requires direct line of sight, and hence is useful only over short (unobstructed) distances.

The Industrial, Scientific and Medical (ISM) radio frequency bands are commonly used for wireless radio communication. These frequencies were originally reserved internationally for non-commercial industrial, scientific and medical purposes. They are:

- 900 MHz band (33.3 cm wavelength);
- 2.45 GHz band (12.2 cm wavelength).

4.1 Wireless Standards

Wireless technologies are often described by their IEEE standard reference. The IEEE Standards Committee for Local and Metropolitan Area Networks (LAN/WANs) is '802'. Its active working groups are shown in Table 1.

TABLE 1 - Working groups of the IEEE 802 Standards Committee. (The groups of interest are shown in bold.)

Active IEEE 802 Local and Metropolitan Area Network Working Groups
802.1 Higher Layer LAN Protocols
802.3 Ethernet
802.11 Wireless Local Area Network
802.15 Wireless Personal Area Network
802.16 Broadband Wireless Access
802.17 Resilient Packet Ring
802.18 Radio Regulatory TAG
802.19 Coexistence TAG
802.20 Mobile Broadband Wireless Access

Working group '11' (802.11) is responsible for the increasingly popular "Wi-Fi" standard IEEE 802.11b and, more recently, 802.11g, which has a much higher data rate of 54Mbps (compared with 11Mbps for 802.11b). Both operate in the ISM frequency bands.

Working group '15' (802.15) is responsible for developing standards for Wireless Personal Area Networks or WPANs™, which are of special interest to wearable computing.

The group's brief states that:

"*The 802.15 WPAN™ effort focuses on the development of consensus standards for Personal Area Networks or short distance wireless networks. These WPANs address wireless networking of portable and mobile computing devices such as PCs, Personal Digital Assistants (PDAs), peripherals, cell phones, pagers, and consumer electronics; allowing these devices to communicate and interoperate with one another.*"

The task groups within 802.15 WPAN™ are:
Task Group 1: (802.15.1) *Bluetooth;*
Task Group 2: Coexistence;
Task Group 3: High data rate;
Task Group 4: (802.15.4) *Sensor networks.*

Both Bluetooth and sensor networks standards also use the ISM frequency bands.

Bluetooth, or IEEE 802.15.1, is a short-range wireless standard which has proved quite popular in commercial devices used primarily for 'local' communication (e.g. between cell phones and headsets). It has a total shared raw data rate of 1Mbps (up to approximately 700kbps for data).

The emerging sensor network standard, or IEEE 802.15.4, is an exciting new standard designed for very, very low power, low cost embedded sensing/processing units, i.e., the type of very small, potentially invisible, embedded computers envisioned by Mark Weiser. It is designed to support data rates of 250 kbps, 40 kbps, and 20 kbps.

The sensor network standard has many challenges – for example, the very low power requirements mean that the network routing protocols must be simple but efficient and yet allow devices to adopt power-conserving sleep modes to suit their needs.

5. FORMS OF WEARABLE COMPUTERS

Most tiered service or quality structures can be compressed into three levels: low, medium and high. For example, 1st class, business and economy, the three basic service classes; and large, medium and small, the three basic sizes.

While many designs may begin with complex levels of service, they often collapse into a simpler three-tier design.

Wearable computers can be mapped onto a three-level scale differentiated by *Processor Performance and Flexibility of Function* (PPaFF).

Table 2 compares the PPaFF levels of wearable computer and relates them to Weiser's original prototypes. As shown, compact, low power microcontrollers provide the processing intelligence for embedded tab-like computers, medium range processors such as the Intel StrongARM support 'poly-functional' pad-like computers and compact high-end desktop equivalents provide the multifunctional board-like computers.

TABLE 2 - PPaFF-scaled forms of wearable computer

PPaFF Scale Processor Performance and Function Flexibility	**Low**	**Medium**	**High**
Weiser's equivalent prototype	Tab	Pad	Board
Processor performance (capacity)	Low	Medium	High
Flexibility of function	Low "Mono-functional" Limited function usually task-specific	Medium "Poly-functional" More flexible, serially replaceable set of functions.	High "Multifunctional" Multiple functions available in parallel.
Microprocessor type	Single chip microcontroller e.g. Microchip 8-bit PIC microcontroller or 16-bit Mitsubishi M16C microcontroller	Mid-range microprocessor e.g. Intel StrongARM as used in PDAs	Higher-end microprocessor e.g. Pentium equivalent PC104-format motherboards (as developed for instrumentation applications).
Typical attention demands made on user	Low May not require a display or just a simple LED or LCD numeric display	Medium Larger graphical display able to display limited information	High Still larger graphical display often requiring a tablet or a head mounted display
Typical power consumption	Low UW (10-6 Watts)	Medium MW (10-3 Watts)	High Several Watts
Operating system	None	Embedded e.g. PocketPC™, Linux™	Full desktop equivalent, e.g. x86 Linux or Microsoft Windows™
Examples of current non-wearable commercial mobile equivalent	Pagers	PDAs, mobile telephones, MP3 players	Laptops, palmtops

Table 2 also approximates the typical form factors, operating system, interface demands of the user, power consumption and commercial devices broadly matching each of the categories.

What is interesting to note is that the more processing power the devices have, the more demands their interfaces generally make of the user's attention. This means that, rather than passively unburdening the user, the systems can actively distract them from the real environment and activities within it. Ideally, the additional processing power would help unburden the user, unobtrusively assisting with useful tasks.

5.1 Examples of PPaFF Forms of Wearable Research Projects and Prototypes

The Pervasive Computing Research Group Lab at Birmingham (http://www.eee.bham.ac.uk/pcg) has several examples of wearable computing projects and prototypes at the three PPaFF levels.

5.1.1 Low PPaFF Systems

The SensVest. The SensVest is a wearable data logging system that senses and records body motion, heart rate and temperature.

Figure 3 - The SensVest - Left the vest and right the electronic enclosure and cable kit.

The processing is carried out by a 16-bit microcontroller, the Mitsubishi M16C. As shown in Figure 3, the The SensVest electronics are contained in a lightweight aluminium case with a simple menu LCD interface system. It can connect directly to a PC or other RS232 serial device, or PDA.

The vest itself has pockets to hold the modules, and tubes for the wiring. The weight is distributed over the back with the lion share of the weight on the shoulder blades for comfort in use.

5.1.2 Medium PPaFF Systems

The StrongARM System. The Intel StrongARM™ processor, recently superseded by XScale, has been used in many PDA and cell phone devices because of its good computing performance (roughly equivalent to a 486 PC) and very low power consumption. This makes it ideal for mid-range, pocket-sized applications. Figure 4 shows the new wearable development platform. It runs a Linux operating system and interfaces to a camera and liquid crystal display.

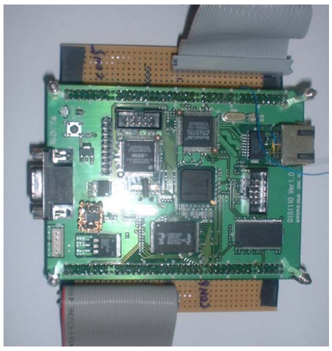

Figure 4 - The DIG StrongARM development board

5.1.3 High PPaFF Systems

The χ3. The χ3 a belt-mountable system, shown in Figure 5, that contains a small compact PC104 Pentium processor board and hard disk. It has the power of a typical desktop computer with all the necessary input and output ports, e.g., connectors for a display and mouse, and a USB connection for high-speed serial devices.

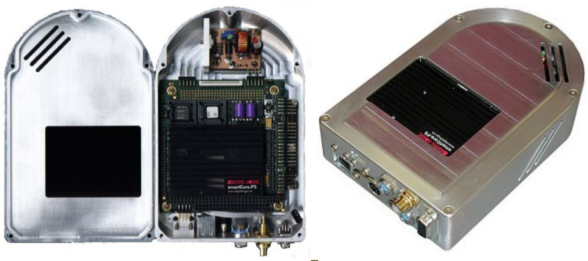

Figure 5 - The χ3; left -open and right -closed. A PC104 Pentium processor in a ventilated aluminium package (the hard disk is beneath the processor board).

Figure 6 - The context-aware χ3+ on trial

The χ3+. The χ3+, a 4-dimensional context-aware device which uses the χ3 platform, is shown in Figure 6. The dimensions are location, body position, object and time; sensed by a GPS receiver, accelerometers and infrared tags. The content displayed for the user is adjusted according to the sensed context (5).

6. ENGINEERING CHALLENGES

With all the advances in wearable computing systems, there are still many engineering challenges to be addressed.

6.1 Wireless and Security

Advances in network communications has given rise to concerns over privacy and security. When computers are networked, there is the potential that information can be compromised.

One of the major problems that initially hampered the roll out of wireless networking was concerns over security. Traditionally, hacking required a physical connection to a network. Now wireless networks, with the right antenna, can be compromised by hackers miles away.

Many implementations of wireless networks do not use any security at all. On the other hand, security can all too easily produce a significant overhead and lead to problems with interoperability.

6.2 Energy Management

Battery technologies are not improving at a fast enough rate (6), as shown in Figure 7, to keep up with the demand for ever more powerful systems. The power consumption of mobile devices is one of the most important design considerations. The size of a wearable system is often a design limitation, which means that the size of the batteries is also constrained together with the heat dissipation that becomes a problem as the size decreases.

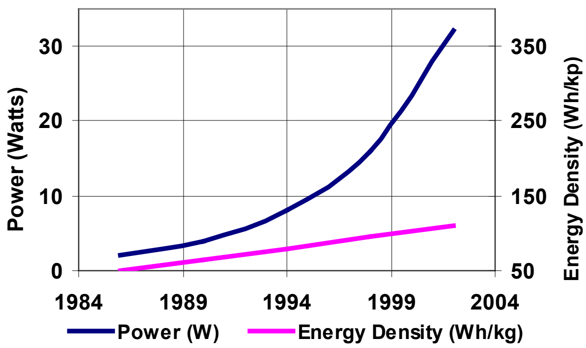

Figure 7 - The Power Performance Gap

Recent advances in technologies such as Lithium-Polymer cell chemistries offer great possibilities because a battery base is no longer needed and the cell can be flat, very light and robust. This leads to some interesting ideas such as embedding the batteries into clothing or other irregular shapes (7). Research in this area will have a profound effect on the future design of wearable systems.

6.3 Display Technology

Displays for the classical wearable computing paradigm are often thought of as a Head Mounted Displays (HMDs). HMDs give rise to all sorts of interesting issues for usability, apart from the obvious obstruction to vision. Typically in mobile systems, the screens consume a large proportion of the total power. New advances such as static electronic paper and other advanced and robust display technologies will enhance the design of future wearables as well as reduce the power consumption.

7.0 SUMMARY

We have classified wearable computing systems into a simple three-level PPaFF scale based on Processor Performance and Flexibility of Function and have summarised the technologies and challenges relevant to Weiser's vision of invisibly embedded computers.

8. REFERENCES

1. Weiser, M., 1991, *A Computer for the 21st Century*, Scientific American, pp 94-100

2."Reaching for Weiser's Vision", Special 1st Issue, Jan 2002, IEEE Pervasive Computing

3. Intel web page on Moore's Law, www.intel.com/research/silicon/mooreslaw.htm

4. Gutierrez, J.A.; Naeve, M.; Callaway, E.; Bourgeois, M.; Mitter, V.; Heile, B., , 2001, *IEEE 802.15.4: a developing standard for low-power low-cost wireless personal area networks* IEEE Network, Vol 15, Iss 5, pp12 –19

5. Bristow, H. W., Baber, C., Cross, J., 2002, *"Evaluating contextual information for wearable computing"* The 6th IEEE International Symposium on Wearable Computers, pp175-186

6. K. Lahiri, A. Raghunathan, S. Dey, and D. Panigrahi, 2002, *"Battery driven system design: a new frontier in low power design,"* ASP-DAC/Int. Conf. VLSI Design, pp261-267

7. I Buchmann, *"The Lithium-Polymer Battery: Substance or Hype?"*, 2003, PowerPulse Power Electronics, Article available on archive http://www.powerpulse.net/powerpulse/archive/aa_080601a1.stm